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Influence of large-scale atmospheric circulation on climate in Latvia

Maris Klavins and Valery Rodinov

Department of Environmental Science, University of Latvia, Raiņa blvd. 19, LV-1586 Rīga, Latvia

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Analysis of the long-term trends in several meteorological parameters (air temperature, precipitation and river discharge) demonstrated significant climatic changes in Latvia. The character of the climate change had a strong seasonal pattern and largely depended on the large-scale atmospheric circulation pattern over Latvia and influence of long-term changes in air temperature (especially in winter), amounts of precipitation, ice regime of rivers and their runoff in Latvia. The climate change signals were related to increased temperature and precipitation at first during winters, and were associated with increased intensity of zonal circulation. Large-scale atmospheric-circulation processes were the most important factor influencing climate in Latvia.

Introduction

Currently, one of the major tasks for climatology is studying climate change character and the factors influencing it. Despite the general consensus about climate change character and driving forces, the local and regional manifestations are being studied to develop a better understanding of the climate change processes and improve the possibilities of developing climate change models. Amongst the major factors influencing climate are large-scale atmospheric circulation, arising from uneven distribution of solar radiation on the Earth's surface, Earth's rotation and the interactions between the atmosphere, hydrosphere and lithosphere, which are influenced by human activities (van Ulden and van Oldenborgh 2006, Huth *et al*. 2008). Large-scale atmospheric circulation is the most important factor influencing climate in northern Europe (Chen 2000, Sepp and Jaagus 2002, Jaagus 2006). Atmospheric circulation processes over central and eastern Europe were first described using three most common circulation patterns: W: westerly circulation, i.e. west–east; E: so-called zonal circulation, i.e. east–west; and C: northerly or meridional circulation (Vangengeim 1952). The possible use of atmospheric circulation indices (ACI) was revitalized by Girs (1971) and other Russian geophysicists. Recently it was demonstrated that the Vangengeim and Girs atmospheric circulation classification scheme allows the analysis and explanation of climatic processes not only in northern and eastern Europe (Aasa *et al*. 2004, Jaagus 2005), but also in significant parts of Siberia (Berezovskaya *et al*. 2005).

Hess and Brezowsky (1969) developed another method for classification of large-scale atmospheric circulation process over central Europe, also known as *Grosswetterlagen* and a recent review of classification possibilities of large-scale atmospheric circulation processes

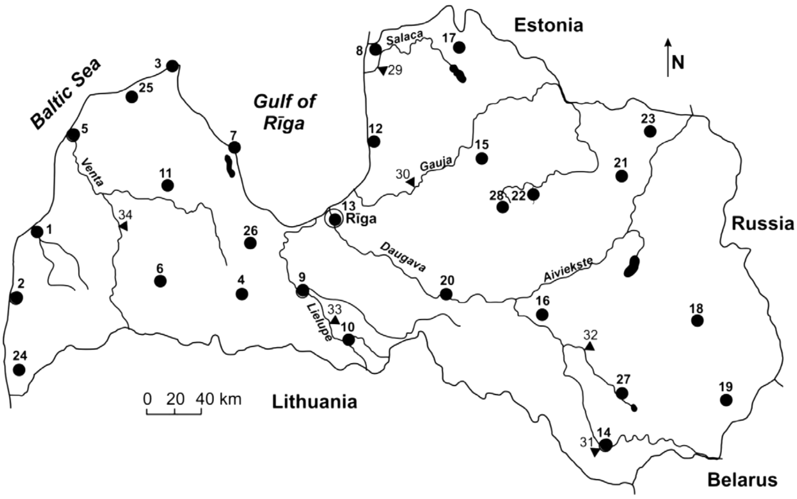

Fig. 1. Locations of meteorological (■) and river gauging stations (▲). Meteorological stations: 1 = Pāvilosta, 2 = Liepāja, 3 = Kolka, 4 = Dobele, 5 = Ventspils, 6 = Saldus, 7 = Mērsrags, 8 = Ainaži, 9 = Jelgava, 10 = Bauska, 11 = Stende, 12 = Skulte, 13 = Rīga-University, 14 = Daugavpils, 15 = Priekuļi, 16 = Zīlāni, 17 = Rūjiena, 18 = Rēzekne, 19 = Dagda, 20 = Skrīveri, 21 = Gulbene, 22 = Zosēni, 23 = Alūksne, 24 = Rucava, 25 = Vičaki, 26 = Praviņi, 27 = Višķi, and 28 = Dzērbene. River gauging stations: 29 = Salaca River (Lagaste), 30 = Gauja River (Sigulda), 31 = Daugava River (Daugavpils), 32 = Dubna River (Siļi), 33 = Lielupe River (Mežotne), and 34 = Venta River (Kuldīga).

was given by Huth *et al*. (2008). It has been demonstrated that an increase in westerly circulation in winter is associated with the North Atlantic Oscillation (NAO) causing higher temperatures and precipitation in northern Europe (Chen and Hellström 1999) and possibly related to greenhouse-gas-driven global climate change. Several studies have shown a close correlation between the NAO index and different indicators of climate change that include temperature, amount of precipitation and snow regime (Loewe and Koslowski 1998, Chen and Hellström 1999, Paeth *et al*. 1999, Uvo 2003). Large-scale atmospheric circulation processes affect air temperature, precipitation and intensity of solar irradiation (Jacobeit *et al*. 2003, Huth *et al*. 2008). However, there is little evidence on impacts of large-scale atmospheric circulation processes on basic climatic indices for Latvia. A significant part of the overall climate system is the hydrological regime closely interplaying with other processes in the climate system and so possibly subjected to climate change processes. At the same time, indicators of the hydrological regime such as river discharge have been comparatively little studied, especially in respect to large-scale atmospheric-circulation processes.

The aim of this study was to analyse changes of large-scale atmospheric-circulation processes over northern Europe and their impact on long-term changes in main climate indicators in Latvia.

Material and methods

The present study was based on daily, monthly and annual data series (1925–2006) of 10 meteorological stations (Fig. 1) obtained from the Latvian Environment, Geology and Meteorology Centre. The daily, monthly and annual precipitation data of the Rīga University station (observations since 1874) was used to investigate the changes in temperature (observations since 1795).

Data on temperature, amount of precipitation, ice regime on Latvian rivers, snow cover and river discharge were used to characterize climate and its changes. Mean annual discharge values, calculated as arithmetic means from monthly records, were used for the trend analysis. Changes in river discharge were determined using the linear trend analysis.

Basic quality and homogeneity control were carried out for all data series as described in Briede *et al*. (2010). Homogeneity of the created precipitation and air temperature series was tested using two statistical homogeneity tests: standard normal homogeneity test (Alexandersson and Moberg 1997) for monthly, seasonal and annual data series; and multiple analysis of series for homogenization (Szentimrey 1997) for daily data series as well as for monthly, seasonal and annual data series. After eliminating several incorrect values, the tests revealed that at $p < 0.05$ there were no grounds for considering any of the precipitation series as non-homogeneous.

Large-scale atmospheric circulation processes have been studied using catalogues of indices (forms) of atmospheric circulation. The Arctic and Antarctic Research Institute (St. Petersburg, Russia) has produced a catalogue of the daily forms of the Atlantic–Eurasia atmospheric circulation processes since 1891 and has successfully provided long-term forecasts. This catalogue has been used to study decadal-scale fluctuations in atmospheric circulation and for calculation of ACI, which have been linked to changes in temperature and precipitation (Vangengeim 1952, Girs 1971) as well as changes in climate and the rotation of the solid Earth (Sidorenkov and Svirenko 1991). To investigate the links to wide-scale climatic forcing, we used the extended NAO index (Luterbacher *et al.* 2002). Classification of the NAO index data is based on the definition of three categories: high (NAO > 1), i.e. strong westerly; normal (NAO ≈ 1); and low (NAO < –1), i.e. weak westerly. To calculate the periodic changes (oscillation) of discharge, moving average (steps of 6 and 10 years) values of discharge data as well as integral curves were utilized. The use of integral curves, which depict differences in discharge for each study year in comparison with mean values for the entire observation period, allows for identification of the pattern of discharge changes. In the calculation, K was used:

$$K = Q_i/Q_0$$

where Q_i is the discharge in year i, and Q_0 is the mean discharge for the entire period of observation.

The sum of normalized deviations from reference climate indicator values has been expressed as $\Sigma(K - 1)$. Integrating of the deviations, the amplitude of the oscillations increases proportionally to the length of the period, with one-sign deviations in the row. The analyses of integral curves allow precise identification of significant change points of low-water and high-water discharge periods. High-water discharge periods were considered to be years for which $K > 1$, and low-water flow periods were $K < 1$. Calculations were carried out using MSExcel, SPSS and Multimk software packages.

A multivariate Mann-Kendall test (Hirsch *et al*. 1982, Hirsch and Slack 1984) for monotone trends in time series of data grouped by sites was chosen for testing trends, as it is a relatively robust method concerning missing data, and lacks strict requirements regarding data heteroscedasticity. The Mann-Kendall test was applied separately to each variable at each site.

Results and discussion

Climatic trends in Latvia

The climatic conditions in Latvia are dominated by transport of cyclonic air masses from the Atlantic Ocean, leading to comparatively high humidity, uneven distribution of atmospheric precipitation through the year, mild winters and moist summers. In general, the spatial heterogeneity of the Latvian climate is determined by physiogeographical features, such as topography, distance to the Baltic Sea, and coverage of forests and mires. Annual mean air temperature decrease in a west–east direction. Annual precipitation in Latvia has a range of 63%–150% of the mean . There is more precipitation during the warm period (April–October) of the year, reaching 63%–70% of the annual total.

More precipitation is common for uplands (> 200 m a.s.l.), and differences between regions can be 250 mm annually. For climate characterization, monthly temperature and precipitation of the Liepāja (SSE Latvia) and Alūksne (NE Latvia) meteorological stations were used (Fig. 2).

Trends of long-term changes in air temperatures in Latvia are constructed from the data of the Meteorological Station Rīga-University (one of the longest observation series in the Baltic Sea

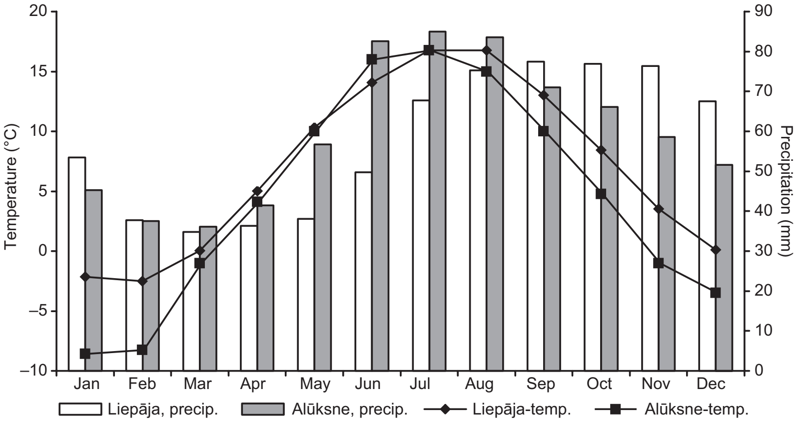

Fig. 2. Seasonal changes in temperature and precipitation in Liepāja (6 m a.s.l.) and Alūksne (198 m a.s.l.) meteorological stations. Mean data for 1948–2007.

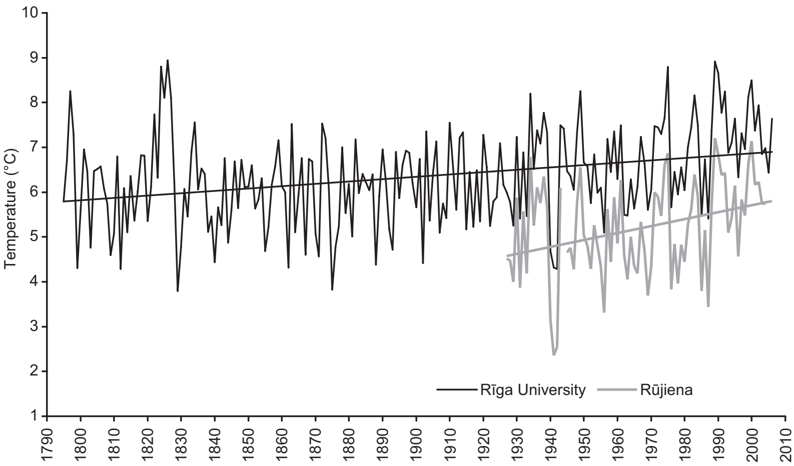

Fig. 3. Long-term changes in air temperature in Rīga and Rūjiena.

area, started in 1795), which are also representative of changes at other Latvian meteorological stations (Fig. 3). Air temperature most significantly increased in the last century, with similar changes in other meteorological stations in Latvia (e.g. Rūjiena) not affected as much by a city microclimate (heat island and city growth)

Table 1. Statistics (Mann-Kendall 1-sided normalized test) for long-term trends in temperature and precipitation in Latvia (1948–2006 annual mean data).

Station	Temperature		Precipitation	
	Value	*p*	Value	*p*
Ainaži	2.08	0.023	–0.39	0.354
Rūjiena	2.73	< 0.001	–0.38	0.352
Rīga	2.77	< 0.001	–0.61	0.274
Ventspils	2.78	< 0.001	0.74	0.235
Daugavpils	1.83	0.035	1.38	0.081

as Rīga (Fig. 3 and Table 1). However, the temperature increase in Rīga was the highest in Latvia, possibly due to impacts of a city microclimate (Table 1).

The long-term increases in air temperature were not evenly distributed within years, e.g. in Rīga (Fig. 4 and Table 2). Here most of the yearly average temperature increase was in winter and spring (October–May), with highest temperature increase in May, April, March and November, December (in descending order).

According to the data from the Meteorological Station Rīga-University for the period 1795–2007, the air temperatures in winter increased by 1.9 °C, in spring by 1.3 °C and in autumn by 0.7 °C. The mean annual temperature increased by 1.0 °C. As compared with the long-term mean (1961–1990), the lowest mean temperature was during 1830–1930 for annual and seasonal temperatures (autumn, spring and summer). Winter season temperatures have increased gradually since the 19th century, and during the 1830–1930 period the long-term minimum was not reached. There have been notable increases in winter and spring air temperatures since the 1970s.

Long-term changes in the amount of precipitation in Latvia did not have a well-expressed trend; the changes at most meteorological stations were statistically non-significant, however, in northern Latvia the amount of precipitation decreased (Fig. 5, Tables 1 and 2).

A significant part of precipitation in the cold seasons was snow, and snow-cover duration and the amount of water accumulated in the snow were major factors influencing river discharge. Our data indicate that the most important changes were during the cold season: the temperature increased, but correspondingly the snow amount and number of days with snow cover decreased (Fig. 6 and Table 3).

At most observation stations, the duration of snow cover was reduced, which was most pronounced in northern Latvia. The change of snow cover duration in the largest cities (most evident in Rīga) was clearly affected by the development of a city microclimate. The trends were affected by the periodicity of the changes in snow regime, influencing both snow cover duration and depth (Fig. 6).

The changes in air temperature, precipitation amount, and accumulated precipitation during winter (snow mass) were among the factors influencing long-term changes in river discharge in Latvia (Fig. 7). Long-term discharge trends for Latvian rivers were not significant (Fig. 7 and Table 4), but the changes in discharge for 1961–2006 were significant and showed increase (except for the Lielupe and Venta rivers).

Long-term trends for seasonal river discharge indicate that most of the increase was during winter (Fig. 8), but also in June–July. The river discharge (for example Daugava, Venta and Lielupe rivers) in winter (December–February) had a significantly increasing trend. There was a particularly significant increase in winter discharge during recent decades.

There were direct links between temperature, ice regime on rivers and their discharge pattern. A decreasing linear trend indicates earlier ice break-up (Table 5 and Fig. 9). The duration

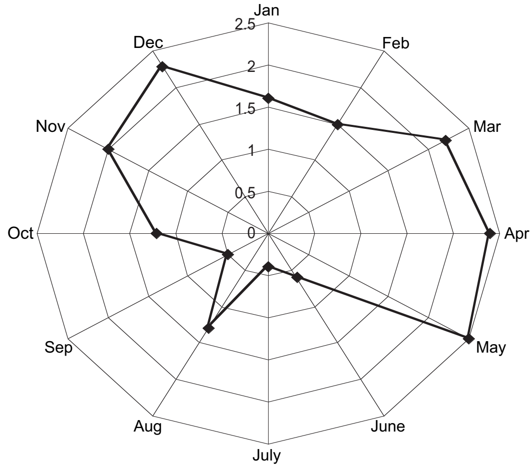

Fig. 4. Long-term changes (1923–2007) in monthly air temperature (°C) at the Meteorological Station Rīga-University.

of ice cover on Latvian rivers during the 20th century (observation periods of 60–77 years, depending on the station) shortened by 2.8–5.1 days per decade.

Effect of large-scale atmospheric circulation on climate and hydrology

Direct measurements of climatic indicators and analysis of atmospheric circulation can be used to characterize climatic processes. Atmospheric circulation can be characterized by circulation indices and the monthly frequency of circulation types. Studies of climate change in Europe (Hurrell and van Loon 1997, Loewe and Koslowski

Table 2. Statistics (Mann-Kendall 1-sided normalized test) for long-term trends in annual mean and seasonal temperatures and precipitation in Rīga.

	Temperature (1795–2006)		Precipitation (1874–2006)	
	Value	p	Value	p
Annual mean	4.6	< 0.001	2.13	0.025
Winter Dec–Feb	2.85	< 0.001	2.11	0.025
Spring Mar–May	5.12	< 0.001	0.23	0.415
Summer Jun–Aug	0.38	0.353	–1.13	0.137
Autumn Sep–Nov	1.9	0.034	2.73	< 0.001
Nov–Mar	3.53	< 0.001	2.29	0.011
Apr–Oct	3.58	< 0.001	0.74	0.234

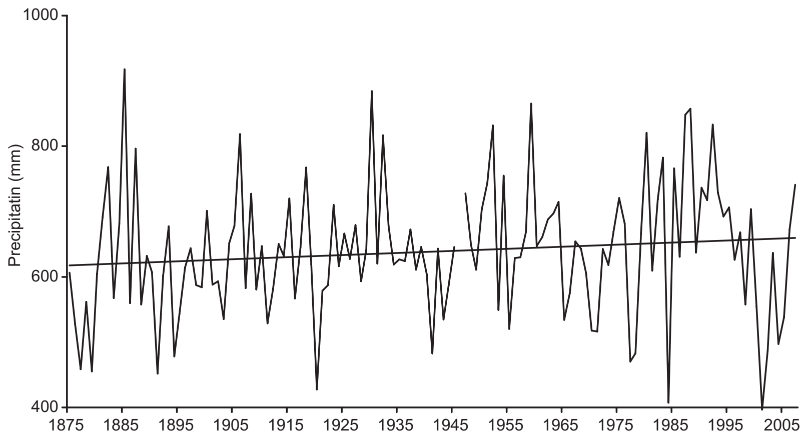

Fig. 5. Long-term changes in annual amount of precipitation at Rīga.

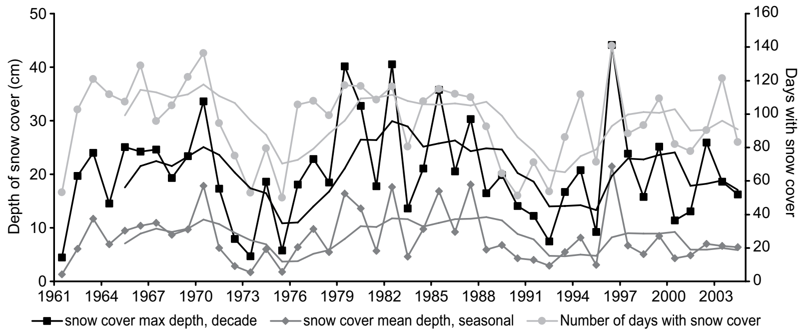

Fig. 6. Long-term changes in the depth and duration of snow cover in Latvia (data smoothed using a five-year moving average).

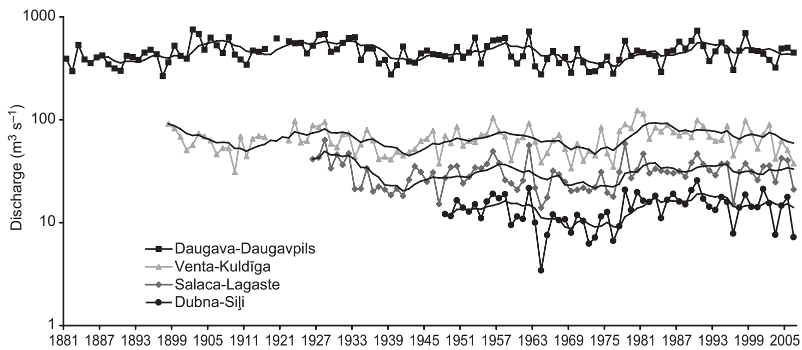

Fig. 7. Long-term changes in discharge for major Latvian rivers.

Table 3. Statistics (Mann-Kendall 1-sided normalized test) for long-term trends in snow cover duration (number of days with snow cover) in Latvia.

Station	Period	Value	p
Rūjiena	1945–2004	–2.39	0.014
Zosēni	1946–2004	–2.52	0.015
Vičaki	1947–1996	–2.12	0.018
Dobele	1950–2004	–1.64	0.045
Ainaži	1947–2004	–1.62	0.048
Rēzekne	1948–2002	–1.56	0.062
Alūksne	1946–2004	–0.74	0.234
Rīga	1945–2004	–0.19	0.419

1998, Chen and Hellström 1999) have most widely used the NAO index, characterizing westerly airflow or the intensity of zonal circulation. The NAO index is defined as the difference in the normalized sea-level pressure between the Azores high and Icelandic low. Vangengeim and Girs (Girs 1971) atmospheric circulation classification system, developed mainly according to the thermobaric wave position in the upper troposphere, shows the dominant directions of air mass transfer and sea-level atmospheric pressure fields. The Hess and Brezowsky large-scale atmospheric-circulation classification system considers: (1) the character of circulation over the North Atlantic; (2) positions of frontal zones; and (3) positions of dominant cyclonic and anticyclonic air masses. Although it focuses on central Europe, it is actually valid over the whole territory of Europe. This classification, which consists of 29 typical circulation patterns and one undetermined case, is valid for Estonia; however, temperature and precipitation data has shown that some patterns bring different weather to central Europe and Estonia (Keevallik and Loitjärv 1999). Post and Tuulik (1999) also showed that for the circulation patterns of zonal and mixed circulation groups the upper flow, and air mass types were similar in central Europe and Estonia; however, for the meridional circulation group there were different air masses over Estonia and central Europe. The flows were similar but Estonia's eastern and northern position is the reason for more transformed and cold air masses (Post and Tuulik 1999).

It is widely recognised that climate change in northern Europe is influenced by large-scale atmospheric processes, mainly by changes in the NAO (Jaagus 2005). For example, changes of precipitation amount in Rīga were well correlated with the NAO index (Fig. 10).

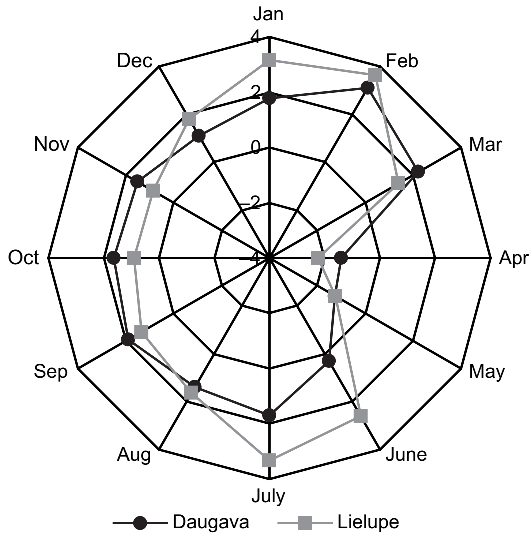

Fig. 8. Mann-Kendall test results for long-term (1961–2006) changes in seasonal discharge of Latvian rivers (Daugava and Lielupe). The trend is considered significant if the test produces values > 2 or < –2

However, transport of the air masses from the North Atlantic is only one of the processes

Table 4. Statistics (Mann-Kendall 1-sided normalized test) for long-term trends in river discharge in Latvia.

River, station	Period	Value	*p*	Period	Value	*p*
Daugava, Daugavpils	1881–2006	0.57	0.286	1961–2006	2.53	0.006
Venta, Kuldīga	1898–2006	1.29	0.098	1961–2006	0.41	0.342
Lielupe, Mežotne	1921–2006	–1.08	0.141	1961–2006	1.64	0.051
Salaca, Lagaste	1927–2006	1.06	0.146	1961–2006	2.66	0.004
Gauja, Sigulda	1940–2006	1.51	0.066	1961–2006	2.06	0.020
Dubna, Siļi	1948–2006	1.38	0.084	1961–2006	2.41	0.008

Table 5. Statistics (Mann-Kendall 1-sided normalized test) for long-term trends in ice break-up events, and correlations between duration of ice cover and NAO winter index (December, January, February and March).

River, station	Period	Value	*p*	Correlation with NAO
Daugava, Rīga	1926–2006	–3.27	< 0.001	–0.56**
Daugava, Daugavpils	1926–2006	–2.06	0.020	–0.52**
Lielupe, Mežotne	1921–2006	–1.06	0.145	–0.54**
Salaca, Lagaste	1927–2007	–1.77	0.038	–0.41*
Venta, Kuldīga	1927–2007	–1.21	0.113	–0.62**
Gauja, Sigulda	1940–2007	–2.87	0.002	–0.55**
Pededze, Litene	1960–2007	–2.46	0.007	–0.60**
Bērze, Baloži	1960–2006	–3.43	< 0.001	–0.70**

* correlation significant at $p < 0.05$ (2-tailed), ** correlation significant at $p < 0.01$ (2-tailed).

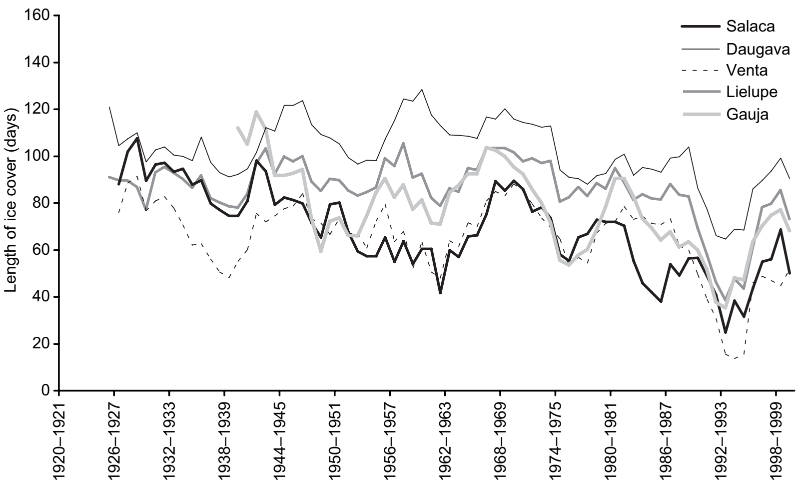

Fig. 9. Duration of ice cover in Latvian rivers. Time series smoothed with a six-year moving average.

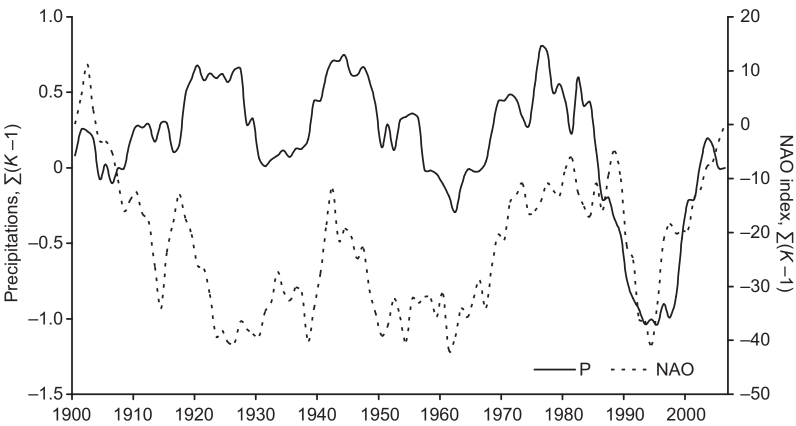

Fig. 10. Normalized integral curves for changes in the annual precipitation in Latvia (Rīga-University) and annual NAO index.

(dominant in winter) that influence climate in Latvia. Analysis of the atmospheric circulation processes over the last century (1900–2000) revealed that the dominant ones (ACI) have longitudinal circulation — either westerly (W) or northerly and easterly (E) — dominating in autumn–winter (80% of the cases; Fig. 11).

The meridional (C: northerly circulation) pattern gained significance only during spring–summer, but occurrence of this circulation pattern does not exceed 1/3 of the overall for a year. At the same time, the long-term analysis of circulation processes (Fig. 11) showed that there were years (e.g. 1902 and 1947) or even periods (e.g. 1900–1902 and 1940–1948) when meridional circulation dominated the overall atmospheric circulation processes.

Starting from the 1950s, the atmospheric circulation process dominated zonal circulation (E + W) at first due to increase in the dominance of southerly and easterly (E) airflow. Starting from the mid-1980s, this ceased and was substituted by increased westerly (W) circulation, accompanied by higher temperatures and increased precipitation in winter (Fig. 12). Cumulative curves of deviations from the reference values (Fig. 12) of atmospheric circulation processes allow for identification of years that, using a century-long scale, could be considered climate turning points (i.e. 1902, 1939 and 1970–1972).

The changes in atmospheric circulation processes have well-expressed periodicity of changes of 6, 10–12 and 15–20 years; possibly periodicity can be related to solar activity and the processes of the Earth's movement in space. In each of these periods one atmospheric circulation type was dominant, except for 1940–1950 when all three airflow patterns had equal impacts. Com-

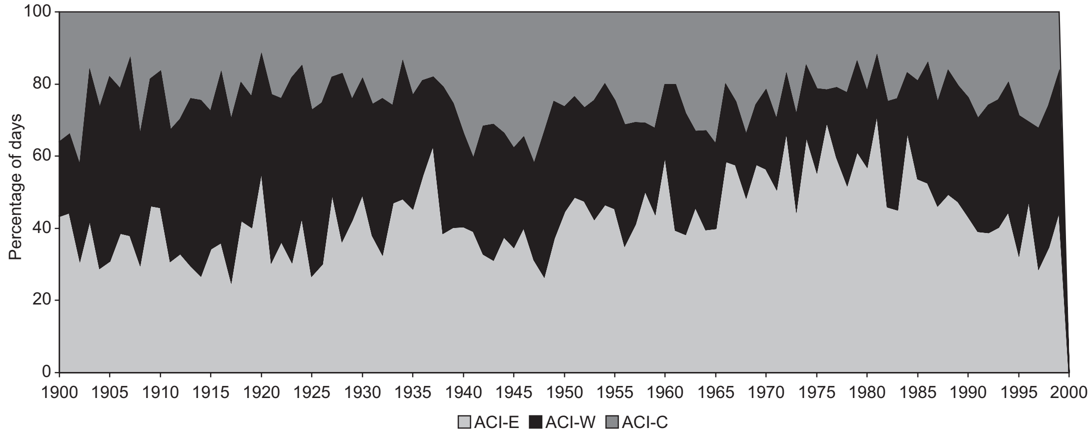

Fig. 11. Long-term changes in large-scale atmospheric circulation processes in Latvia (Baltic region). ACI-E: atmospheric circulation indices easterly type, ACI-W: atmospheric circulation indices westerly type, ACI-C: atmospheric circulation indices northerly type.

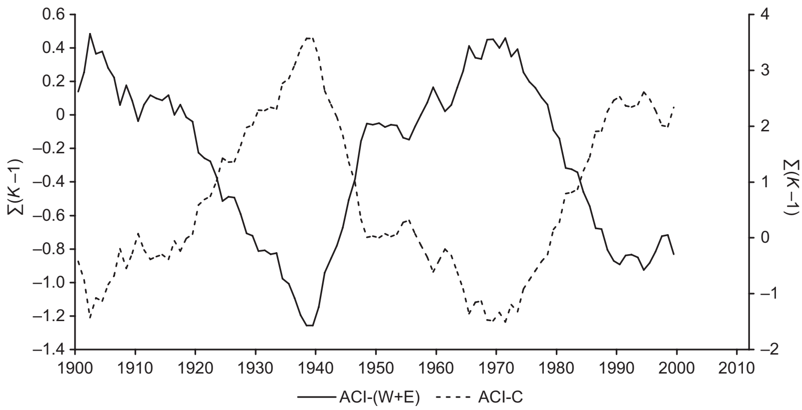

Fig. 12. Integral curves for atmospheric circulation indices for zonal (W + E) and meridional (C) atmospheric-circulation anomalies.

parative analysis of zonal (W + E) and meridional (C) atmospheric circulation types, summing up yearly anomalies for corresponding circulation pattern, allowed for the generation of integral curves demonstrating the centennial changes in air mass transport during three periods (30–33 years) when zonal airflow was influenced by meridional circulation patterns (Fig. 12).

Analysis of changes in atmospheric circulation processes explains variability of meteorological conditions in Latvia (temperature, precipitation, length of snow cover, ice regime on rivers, and river discharge). Frequently, closer correlations were found for winter, when zonal circulation processes dominated (Tables 6 and 7). Correlations between atmospheric circulation processes and climate indicators in spring–summer–autumn were less common (Fig. 13; *see* also Klavins *et al*. 2007).

The long-term changes in atmospheric circulation patterns were consistent with long-term changes in river discharge, e.g. for the Venta River. The same pattern was common to the largest river in Latvia (Daugava) as well as for mid-sized rivers (Lielupe, Gauja and Salaca) where there was a positive correlation with zonal circulation (W) indices. However, there was a negative correlation with meridional circulation type C for the Venta River discharges (Table 7 and Fig. 9).

Conclusions

Our results suggest that the impact of airflow from the North Atlantic in spring–summer–autumn was not as important as the role of the meridional atmospheric circulation processes.

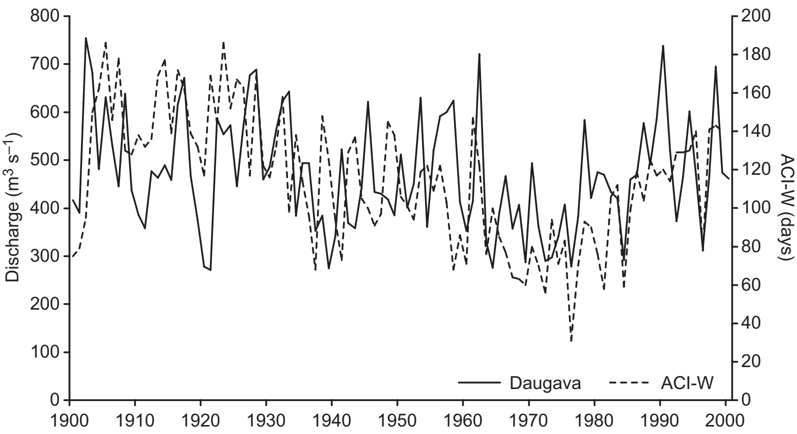

Fig. 13. Long-term changes in the Daugava and Venta discharge and character of atmospheric circulation processes.

The period April–September covers the spring transition in the northern hemisphere (end of March to early June) from winter to summer atmospheric circulation (which is more dependent on solar radiation), then the summer and the transition back to winter circulation. During summer, the westerly circulation is at its weakest, and during spring/autumn, when it gradually weakens/intensifies, meridional circulation develops more often, whereby either arctic or warm mid-latitude air masses arrive in Latvia. At the same time, if westerly airflow was associated with increased transport of warmer air masses and increased precipitation, then with dominant meridional circulation the transfer of air masses from North Atlantic could be either blocked or be a source of increased precipitation. In general, meridional circulation is mostly responsible for blocking of atmospheric circulation.

The analysis of large-scale atmospheric circulation processes allows for identification of years that, using a centennial scale, can be considered climatic turning-points (i.e. 1902, 1939 and 1970–1972) associated with significant changes in climate indicators (e.g. winter temperatures and amount of precipitation).

Table 6. Correlation of the river discharge in Latvia with the large-scale atmospheric-circulation processes.

River, station	Period	ACI-E	ACI-W	ACI-C
Daugava, Daugavpils	1900–2000	–0.35**	0.36**	0.04
Venta, Kuldīga	1900–2000	0.04	0.14	–0.25*
Lielupe, Mežotne	1921–2000	–0.27*	0.38**	–0.08
Gauja, Sigulda	1940–2000	–0.16	0.40**	–0.21
Salaca, Lagaste	1927–2000	–0.16	0.43**	–0.26*

* correlation significant at $p < 0.05$ (2-tailed), ** correlation significant at $p < 0.01$ (2-tailed).

Table 7. Correlation between atmospheric circulation indices (Nov–Mar), snow cover parameters and winter temperature in Latvia.

	Days with snow cover			Depth of snow cover			Temp. (°C) Dec–Feb
	Ainaži	Alūksne	Rūjiena	Ainaži	Alūksne	Rūjiena	Rūjiena
ACI-E	0.46**	0.32*	0.40*	0.33*	0.47**	0.33*	–0.24*
ACI-W	–0.56**	–0.28*	–0.29*	–0.45**	–0.54**	–0.38**	0.46**
ACI-C	–0.08	–0.17	–0.06	–0.01	–0.12	–0.08	–0.19

* significant at the 0.05 level (1-tailed),** significant at the 0.01 level (1-tailed).

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